Low Hubble Constant from Type Ia Supernovae by van den Bergh's Method

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An interesting way to calibrate the absolute magnitudes of remote Type Ia supernovae (SNe Ia) that are well out in the Hubble flow[1], and thus determine the value of the Hubble constant, $\mathbf{H_0}$, has been introduced by van den Bergh[2]. His approach relies on calculations[3] of the peak absolute magnitudes and broad–band colors for SN Ia explosion models. It does not require any corrections for extinction by interstellar dust, and no SNe Ia are excluded on grounds of peculiarity. Within the last few years distances have been determined to the parent galaxies of six SNe Ia by means of Cepheid variables[4−10]. Cepheid–based distances also have become available for three other SNe Ia if one is willing to use the distance to a galaxy in the same group in lieu of the distance to the parent galaxy itself. Here we determine the value of $\mathbf{H_0}$ in a way that is analogous to that of van den Bergh, but now using Cepheid–based distances instead of calculated light curves. We obtain $\mathbf{H_0 = 55 \pm 5}$ **km s**$^{\mathbf{-1}}$ **Mpc**$^{\mathbf{-1}}$. This value, with $\mathbf{\Lambda = 0}$ and $\mathbf{\Omega = 1}$, corresponds to a cosmic expansion time of $\mathbf{12 \pm 1}$ Gyr, which is consistent with several recent determinations of the ages of globular clusters.

van den Bergh noted that the explosion–model light curves obey a relation between the peak visual absolute magnitude M_V and the $B - V$ color, with a slope that is nearly the same as that of the standard extinction law, $A_V/E(B - V) = 3.1$. Consequently one can define a parameter

$$M_V^* = M_V - 3.1(B - V)$$

which is, to a first approximation, independent of both extinction and supernova model. From the models, van den Bergh derived values of M_V^* ranging from -19.60 ± 0.05 to -19.75 ± 0.02 depending on which weights were assigned to the various models. For the 13 real SNe Ia in the CTIO remote sample, which is well out in the Hubble flow ($3000 \leq cz \leq 30,000$ km s^{-1}), van den Bergh found

$$M_V^* = -19.59 \pm 0.11 + 5log(H_0/60 \text{ km s}^{-1} \text{ Mpc}^{-1})$$

and therefore obtained values of H_0 ranging from 60 ± 3 to 55 ± 3 km s^{-1} Mpc^{-1}. These values depend on the models and the light–curve calculations but they are independent of any astronomical calibration.

TABLE 1 Cepheid–calibrated type Ia supernovae

SN	galaxy	B	V	B-V	μ	M_V
1937C	IC 4182	8.71±0.14	8.72±0.06	-0.03±0.13	28.36±0.09	-19.64±0.11
1960F	NGC 4496	11.58±0.05	11.49±0.15	0.09±0.16	31.10±0.13	-19.61±0.20
1972E	NGC 5253	8.61±0.21	8.61±0.12	0.00±0.09	28.08±0.10	-19.47±0.16
1981B	NGC 4536	12.04±0.04	11.98±0.04	0.04±0.06	31.10±0.13	-19.12±0.14
1986G	NGC 5128	12.45±0.05	11.40±0.05	1.05±0.07	28.08±0.41	-16.68±0.42
1989B	NGC 3627	12.34±0.05	11.99±0.05	0.35±0.07	30.32±0.16	-18.33±0.17
1990N	NGC 4639	12.70±0.05	12.61±0.05	0.09±0.07	32.00±0.23	-19.39±0.24
1991T	NGC 4527	11.64±0.05	11.50±0.04	0.14±0.06	31.10±0.16	-19.60±0.16

Data for the Cepheid–calibrated SNe Ia for which the peak B and V magnitudes are known are listed in Table 1. (SN 1895B in NGC 5253 cannot be used here because only B is known.) Sources of the data are as follows. SN 1937C: B and V are from Schaefer[11] and the distance modulus, μ, is from Saha et al.[6]. The uncertainty in $B - V$ is less than would be obtained from the quadrature sum of the uncertainties in B and V because the uncertainties in B and V are correlated. SN 1960F: B, V, and μ are from Saha et al.[10]. Somewhat different values, $B = 11.77 \pm 0.07$ and $V = 11.51 \pm 0.18$, have been reported[12] but these are based on less information than those of Saha et al. and they make SN 1960F suspiciously red, with $B - V = 0.26$ (although with an uncertainty of ± 0.19). SN 1972E: B and V are from Hamuy et al.[1], the uncertainty in $B - V$ takes into account that the uncertainties in B and V are correlated, and μ is from Saha et al[7]. SN 1981B: B and V are from Schaefer[13] and μ is from Saha et al[9]. SN 1986G: B and V are from Phillips et al.[14] and μ is equated to that of SN 1972E because their parent galaxies, NGC 5128 and NGC 5253, are both members of the Centaurus group, but with an additional uncertainty of ± 0.4 for SN 1986G because

these two galaxies are separated by 11.8 degrees on the sky. (SN 1986G will not enter into our adopted result, but its very red $B-V$ of 1.05 will help to illustrate the validity of the procedure.) SN 1989B: B and V are from Wells et al.[15] and μ is equated to that of NGC 3368[16] because NGC 3627, the parent galaxy of SN 1989B, and NGC 3368 are fellow members of the Leo spur[17]. An additional uncertainty of ± 0.14 has been included for SN 1989B to allow for possible differences in distance between NGC 3627 and NGC 3368 and 0.05 has been added for the HST "long exposure" effect[8]. SN 1990N: B and V are from Leibundgut et al.[18] and μ is from Sandage et al[8]. SN 1991T: B and V are from Phillips et al.[19] and μ is equated to that of SNe 1960F and 1981B because their parent galaxies are thought to be members of the same compact group[20,21]). SN 1991bg is not in Table 1 but it is plotted as a special symbol. $B = 14.70 \pm 0.10$ and $V = 13.95 \pm 0.02$ are from Leibundgut et al[22]. SN 1991bg, with its red $B-V$ of 0.75, is considered only to help illustrate the validity of the procedure. It will not be used in the analysis because there is no Cepheid–based distance to NGC 4374, a Virgo elliptical galaxy. For the illustration we use $\mu = 31.62 \pm 0.35$ obtained[21] from the "SEAM" spectrum–fitting procedure[23−25] which gives a distance to SNe 1981B that is in excellent agreement with its Cepheid–based distance[21].

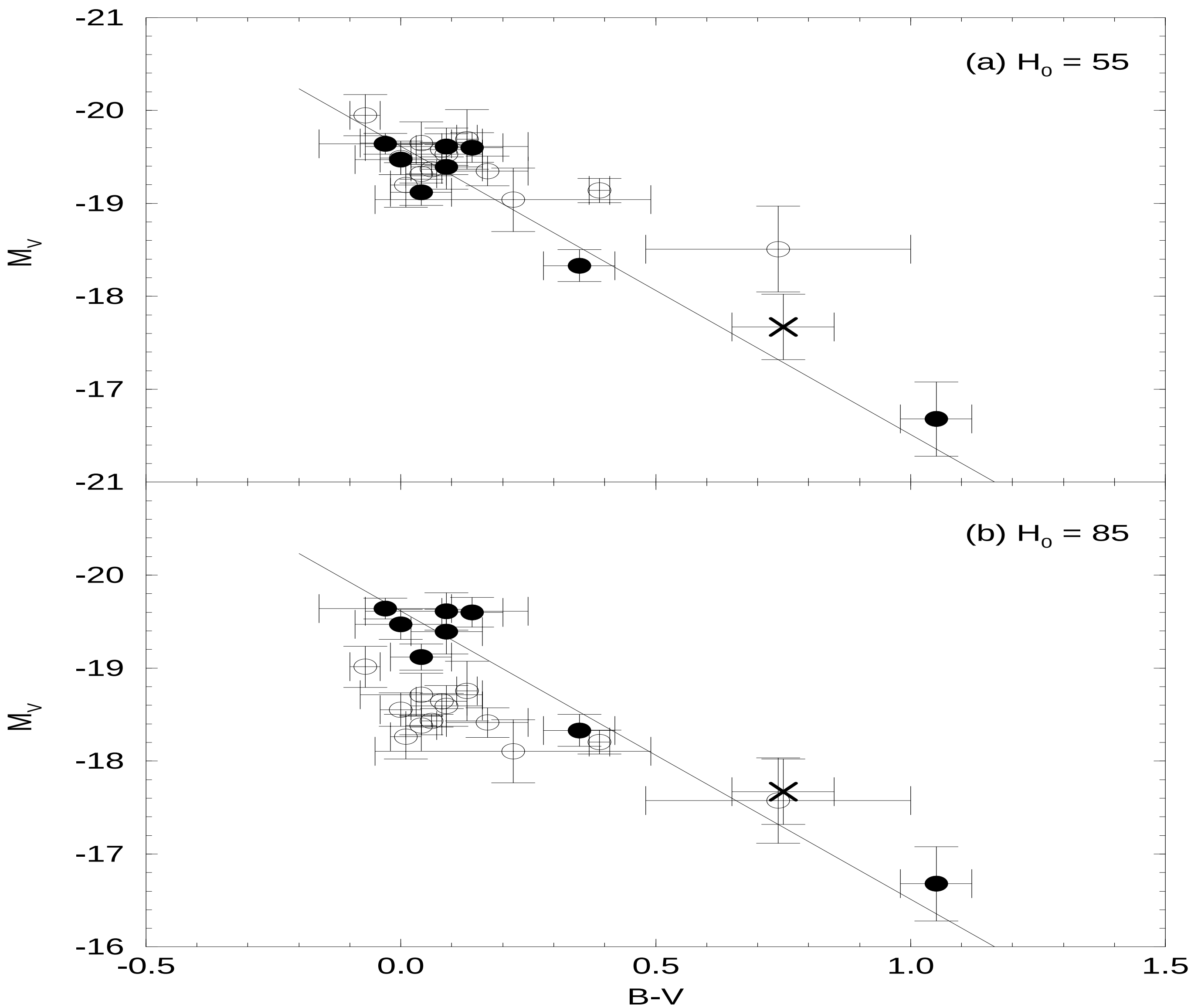

FIG. 1. a Peak visual absolute magnitude, uncorrected for extinction, is plotted against $B-V$ for Cepheid–calibrated SNe Ia (filled circles), SN 1991bg (cross), and the CTIO sample of remote SNe Ia (open circles). For the latter, $H_0 = 55$ km s^{-1} Mpc^{-1} has been used. The straight line has the extinction slope, $A_V/E(B-V) = 3.1$. b Using $H_0 = 85$ instead of 55.

M_V, uncorrected for extinction, is plotted against $B - V$ in Fig. 1a. The eight Cepheid–calibrated SNe Ia are plotted as filled circles and the 13 SNe Ia of the CTIO remote sample are plotted as open circles. The data points tend to lie along the extinction line. SN 1989B, intrinsically normal but extinguished[15], SN 1991bg, unextinguished but intrinsically dim and red[26,22], and SN 1986G, intrinsically dim and red *and* extinguished[14], all lie very near the extinction line. SN 1990Y, probably intrinsically normal but extinguished[1], and SN 1992K, intrinsically dim and red[27], are not far off. The tendency of real SNe Ia, whether extinguished and/or intrinsically dim and red, to lie near the extinction line shows that this approach is a useful one. It also supports the general validity of the explosion–model light–curve calculations[3].

Now we turn our attention to the cluster of bright, blue SNe Ia having $M_V \leq -19$ and $B - V \leq 0.2$. These are so tightly clustered that no correlation between M_V and $B - V$ is readily apparent. We suspect that the *intrinsic* properties of these SNe Ia would show a correlation, because there are good reasons to think that SN 1991T is significantly extinguished and intrinsically the bluest and brightest SN Ia yet discovered[28], and SN 1981B, the faintest of these clustered data points at $M_V = -19.12$, was mildly extinguished (e.g., M. M. Phillips, personal communication). But for the present procedure, these opinions about the extinction make no difference. If we restrict our attention to the clustered data points and match the 11 SNe Ia of the CTIO sample (for which $M_V^* = -19.43 \pm 0.07 + 5log(H_0/60)$) to the six Cepheid–calibrated SNe Ia (for which $M_V^* = -19.61 \pm 0.12$), we obtain $H_0 = 55 \pm 4$ km s^{-1} Mpc^{-1}. Omitting SN 1937C on the grounds that it's B and V are disputed[29,30] would not change the result at all, nor would the omission of the six SNe Ia of the CTIO sample that were discovered more than 10 days after maximum light. Including the dimmer and redder SNe 1989B, 1990Y, 1992K, and 1986G, which we do not favor because it would be stretching the method too far, would give $H_0 = 58 \pm 3$ km s^{-1} Mpc^{-1}.

We adopt $H_0 = 55 \pm 5$ km s^{-1} Mpc^{-1} from this method, which does not make use of any extinction corrections and does not entail excluding any SNe Ia on grounds of peculiarity. Fig. 1b is just like Fig. 1a except that H_0 is set to 85 rather than 55 km s^{-1} Mpc^{-1}. The few red and dim SNe Ia actually fit better, but *all* of the bright, blue Cepheid–calibrated SNe Ia are brighter than *all* of the bright, blue SNe Ia of the CTIO sample. This is entirely unsatisfactory, and $H_0 = 85$ is excluded. To the extent that there is scatter in the relation between M_V and $B - V$, and that the CTIO sample of remote SNe Ia is magnitude–selected to a greater degree than the sample of nearer Cepheid–calibrated SNe Ia, then the true value of H_0 may be a little *lower* than we have obtained here.

van den Bergh[2] suggested that the conflict between the low value of H_0 that he obtained using models of SNe Ia, and higher values obtained by others using Cepheid–based distance determinations to a few spiral galaxies in the Virgo cluster complex, implied that unless Cepheids are unreliable distance indicators the models must be either too blue or too bright. However, *the present result of $H_0 = 55 \pm 5$ km s^{-1} Mpc^{-1}, obtained by the method of van den Bergh but using Cepheids rather than models, gives the same low value of H_0.* This shows that the fault lies not with the models, nor with the Cepheids, but with the hazardous route through the Virgo cluster complex[21,31].

The present result of $H_0 = 55 \pm 5$ km s^{-1} Mpc^{-1} also is in excellent agreement with detailed spectrum fitting of SNe Ia using fully relativistic, NLTE calculations[24,25,21]; with methods based on ^{56}Ni radioactivity[21]; with a straightforward standard–candle treatment[8]; with a treatment[12] that takes the effects of a putative magnitude–decline correlation into account; and with a result[32] that distinguishes between SNe Ia in blue and red galaxies. The impressive agreement between Cepheid–based and physically–based calibrations indicates that future modifications to the Cepheid period–luminosity law will not have strong effects on the value of H_0 obtained from SNe Ia. It is difficult to see how a lingering controversy between "high" (e.g., 85) and "low" (e.g., 55) values of H_0 can be maintained. The situation is asymmetric. SNe Ia require a low value and they cannot be reconciled with a high value. Which method that is said to favor a high value cannot be reconciled with the low value that is required by SNe Ia?

$H_0 = 55 \pm 5$ km s^{-1} Mpc^{-1}, with $\Lambda = 0$ and $\Omega = 1$, corresponds to a universal expansion age of 12 ± 1 Gyr, which is consistent with some recent determinations of the ages of globular clusters[33–37], and not inconsistent with a recent estimate of the age of an ultra–metal–poor star based on its content of radioactive thorium[38].

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